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FINAL REPORT

"Plasma Physics of Planetary Magnetospheres"

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This is a final report summarizing the research activity and publications resulting from NASA grant NAGW–3190. The organization of the report is as follows:

A. Published Papers:

1) Barbosa, D. D., Thermal structure of ions and electrons in Saturn 's inner magnetosphere, *J. Geophys. Res.*, 98, 9335, 1993.

ABSTRACT

A theoretical model of thermal ion and electron temperatures in Saturn 's inner magnetosphere is presented. The rationale for the model is based on a fast mode of radial diffusive transport in which the diffusion time scale varies with distance as $\tau_D = 2 \times 10^6$ s $(6/L)^3$. Such a model provides a conceptual organization to the energy balance problem in that the plasma residence time in the region L > 4.5 is short compared to the time scale for Coulomb energy exchange and radiative losses whereas the opposite is true in the region L < 4.5. This condition implies that in the Dione-Tethys plasma torus the ion and electron temperatures reflect their initial values upon creation out of the neutral H_2O cloud distributed throughout the region. Oxygen ions thus have a temperature corresponding to local pickup by the magnetic field and a large perpendicular temperature anisotropy while electrons have a temperature corresponding to that of ionization secondaries created by electron impact dissociation/ionization of H_2O by the ambient hot electron population. In the collisional L < 4.5 regime the ion temperature is controlled by local pickup from $O^+ - O$ charge exchange while the electron temperature is controlled by heating from thermal O^+ ions against radiative losses from electron-excited OII. A calculation of the off-equatorial behavior of density and temperature in the Dione-Tethys torus based on the assumption of a constant ion temperature anisotropy along field lines is also described. The model successfully reproduces the decrease with latitude in electron and O^+ temperatures which occur as a result of the interaction of electrons with the ambipolar electric potential and O^+ ions with the centrifugal potential.

This paper develops a theoretical model of the plasma structure known as the Dione-Tethys torus. There have been several outstanding theoretical problems in constructing a viable model of the D-T torus. First, the energy balance was never understood well so that no explanation for the observed ion and electron temperatures was available. Second, the latitudinal structure of the torus, in particular the fact that the ion and electron temperatures decrease with latitude away from the equator, was not understood. And thirdly, the radial structure of density and temperature inside L = 6 was an issue requiring a settlement. All of these theoretical questions have been resolved in Paper #1 which pursues the implications and consequences of the so-called fast diffusion hypothesis which states that radial plasma transport is of crucial importance in determining the plasma state of the inner magnetosphere. Fast diffusion is the one assumption that unifies the theoretical description of ion and electron density and temperature and their dependence on radial distance and latitude. This paper is regarded as a major breakthrough in the theoretical modelling of Saturn's magnetosphere and may well have an impact on other planetary magnetospheric studies as well.

2) Barbosa, D. D., Theory and observations of electromagnetic ion cyclotron waves in Saturn's inner magnetosphere, *J. Geophys. Res.*, 98, 9345, 1993.

ABSTRACT

High-resolution Voyager 1 magnetic field observations of Saturn's inner magnetosphere are examined for the presence of ultralow frequency waves. Quasi-circular left-hand polarized transverse oscillations are found in the near equatorial region of 5–7 R_S with a wave period ~ 10 s and peak amplitude ~ 2 nT. The wave is identified as the electromagnetic oxygen cyclotron mode occurring at a frequency just below the O^+ ion cyclotron frequency. The properties of the waves are very similar to those found by Smith and Tsurutani (1983) using Pioneer 11 data. A theoretical model of wave excitation based on gyroresonant coupling through a temperature anisotropy of O^+ pickup ions is developed which accounts for the principal features of the wave spectrum. The theory and observations form the basis for the hypothesis that wave-particle interactions provide a level of scattering commensurate with the weak pitch angle diffusion regime but nonetheless one that regulates and maintains a constant thermal anisotropy of ions along the magnetic field. Arguments are also presented that O^+ was the dominant thermal ion of the Dione-Tethys plasma torus at the time of the Pioneer 11 encounter the year previous to the Voyager 1 measurements.

This paper searches Voyager 1 high-resolution magnetometer data for evidence of ion cyclotron waves in the Dione-Tethys torus. Evidence for left-hand polarized waves propagating along the magnetic field with periods ~ 10 s was found by Pioneer spacecraft investigators the previous year. The Voyager data search proved successful in confirming the presence of the waves. The theory advanced in the paper attributes the waves to a thermal anisotropy of O^+ pickup ions in the torus and the model calculations give a good accounting of the wave properties. In particular, the peak frequency of the spectrum and the upper frequency cutoff are well-explained on the basis of the O^+ model.

3) Barbosa, D. D. and W. S. Kurth, On the generation of plasma waves in Saturn's inner magnetosphere, *J. Geophys. Res.*, 98, 9351, 1993.

ABSTRACT

Voyager 1 plasma wave measurements of Saturn's inner magnetosphere are reviewed with regard to interpretative aspects of the wave spectrum. A comparison of the wave emission profile with the electron plasma frequency obtained from in situ measurements of the thermal ion density shows good agreement with various features in the wave data identified as electrostatic modes and electromagnetic radio waves. Theoretical calculations of the critical flux of superthermal electrons able to generate whistler-mode waves and electrostatic electron cyclotron harmonic waves through a loss-cone instability are presented. The comparison of model results with electron measurements shows excellent agreement lending support to the conclusion that a moderate perpendicular anisotropy in the hot electron distribution is present in the equatorial region of L = 5–8.

This paper along with Paper #2 addresses the wave phenomena found in the D-T torus. Paper #2 deals with ultra low-frequency electromagnetic modes while Paper #3 treats the very low-frequency regime of plasma waves including whistler-mode hiss and chorus as well as electrostatic electron cyclotron harmonic (ECH) waves. The theoretical aspect of the paper demonstrates conclusively that a superthermal electron distribution with a pitch angle anisotropy of order 1 can excite both the whistler-mode waves and the ECH waves. A comparison of in situ electron measurements with predictions of the theoretical model shows excellent agreement.

4) Barbosa, D. D., Transverse particle acceleration and diffusion in a planetary magnetic field, *J. Geophys. Res.*, 99, 8593, 1994.

ABSTRACT

A general model of particle acceleration by plasma waves coupled with adiabatic radial diffusion in a planetary magnetic field is developed. The model assumes a spectrum of lower hybrid waves is present to resonantly accelerate ions transverse to the magnetic field. The steady state Green's function for the combined radial diffusion and wave acceleration equation is found in terms of a series expansion. The results provide a rigorous demonstration of how a quasi-Maxwellian distribution function is formed in the absence of particle collisions and elucidate the nature of turbulent heating of magnetospheric plasmas. The solution is applied to the magnetosphere of Neptune where a number of examples is given illustrating how the spectrum of pickup N^+ ions from Triton evolves.

This paper considers the acceleration of ions by electrostatic waves near the lower hybrid frequency in a model that includes wave-particle interactions and simultaneous adiabatic radial diffusion in a dipole magnetic field. A general solution for the phase space distribution function is obtained for an arbitrary distribution of particles injected into the magnetosphere. The source may inject either pickup ions with an energy corresponding to the local corotation speed or thermal ions with an energy reflecting the temperature of their place of origin, e.g., a satellite's ionosphere. The solution shows the interesting result that for wave activity localized to the inner magnetosphere a high-energy tail can be formed there and preserved as the ions diffuse to the outer magnetosphere. The model is applied to the magnetosphere of Neptune where Voyager plasma observations showing a large abundance of heavy ions can be explained as N^+ ions that are created out of a Triton atomic neutral cloud extending over a distance $\Delta R \simeq 10\text{-}14\ R_N$ and then are transported by diffusion throughout the magnetosphere.

5) Barbosa, D. D., Theory of electron acceleration by lower hybrid waves in the Io plasma torus of Jupiter, *J. Geophys. Res.*, 99, 11,079, 1994.

ABSTRACT

A theoretical model of superthermal electron acceleration in the Io plasma torus is developed. The model assumes that sulfur and oxygen ions are created out of Io 's extended neutral cloud forming a ring distribution in velocity space which is unstable to the growth of lower hybrid waves traveling perpendicular to the magnetic field. The waves dissipate through Landau damping by plasma electrons accelerating them to kiloelectron volt energies. The present model computes the electron distribution function evolving under the action of the lower hybrid waves with the simultaneous occurrence of Coulomb collisions. The results show that for moderate electric field amplitudes characteristic of the lower hybrid waves observed there a power law velocity dependence is generated along with a quasi-isotropic pitch angle distribution due to Coulomb collisions. The power law extends up to a characteristic speed where the electron energy equals the pickup ion energy. At higher energies an exponential distribution is prevalent with an effective temperature proportional to the wave acceleration efficiency. The model has a wide applicability to space and astrophysical plasmas where the presence of hot electrons gives rise to anomalous ionization effects.

This paper examines the physics of how hot electrons are generated in magnetized plasmas whose source is a neutral cloud in motion relative to the plasma. The ionization of the cloud results in the generation of pickup ions with a gyrospeed corresponding to the relative velocity of the neutrals and the plasma. As a result, a ring distribution in velocity space is formed which, as is well known, is unstable to the generation of a variety of plasma modes, most notably, the lower hybrid mode. Paper #4 investigated the effects of lower hybrid waves on the ion distribution. A concurrent effect is the acceleration of electrons along the magnetic field, the electron interaction being the primary dissipation channel of the waves. The model developed in Paper #5 computes the distribution function with Coulomb electron-electron collisions acting simultaneously with the wave acceleration. The paper shows that in the limit of small wave electric field amplitudes a superthermal tail is formed in the distribution having a power law velocity dependence, the exponent of which is proportional to the mean square electric field amplitude. The model is believed to be highly relevant to the chemistry of astrophysical gaseous nebulae that share properties common to the Io plasma torus, a theme developed further in Paper #6.

6) Barbosa, D. D., Neutral cloud theory of the Jovian nebula: Anomalous ionization effect of superthermal electrons, *Astrophys. J.*, 430, 376, 1994.

ABSTRACT

The standard model of the Jovian nebula postulates that its particle source is the extended cloud of neutral sulfur and oxygen atoms that escape from the satellite Io and become ionized through electron impact from the corotating plasma. Its energy source is the gyroenergy acquired by newly formed pickup ions as they are swept up to corotation velocity by the planetary magnetic field. Elastic collisions between plasma ions and electrons cool the ions and heat the electrons while inelastic collisions cool the electrons and excite the ions to radiate intense line emission which is primary energy loss mechanism for the plasma. This neutral cloud theory of the Io plasma torus as it has come to be known has been the subject of recent criticism which asserts that the theory cannot account for the observed charge state of the plasma which features O^+ and S^{2+} as the dominant ions. It is shown in this work that the inclusion of a small population of superthermal electrons is required to achieve the correct ion partitioning among various charge states. The superthermal electrons are an essential element of the theory: they are a consequence of the highly nonthermal velocity distribution of pickup ions generating plasma waves which dissipate by accelerating hot electrons to kiloelectron volt energies. Coupled ionization and energy balance equations are solved for a homogenous plasma model featuring the addition of a superthermal electron population. The results of the analysis show excellent agreement with the observations. It is also argued that the anomalous ionization effect of the superthermal electrons is responsible for the overall spatial bifurcation of the nebula into a hot multiply-charged plasma region outside of 5.7 Jovian radii and a cool singly-ionized plasma inside this distance.

This paper deals with the physics and chemistry of the Jovian nebula (a. k. a. Io plasma torus) in a computer model that solves the coupled ionization and energy balance equations for a source of particles originating in the extended neutral clouds of Io. The key aspect of the present calculation is the inclusion of a small concentration of superthermal ~keV electrons which do not place a large burden on the energetics of the torus but have a large influence on the ionization balance. The numerical solution demonstrates that with a small admixture ~0.2% of hot electrons the model is able to reproduce the observations of a hot multiply charged heavy ion plasma conforming to the requirement that $[S^+]/[S^{2+}] \lesssim 1$. The present work establishes neutral cloud theory as a viable description of Io torus physics and chemistry and paves the way for a inhomogeneous model that includes radial transport to be developed in the upcoming years.

7) Barbosa, D. D., Stochastic acceleration of energetic ions in Jupiter's magnetosphere, *J. Geophys. Res.*, 99, 13,509, 1994.

ABSTRACT

An equation governing the combined radial diffusion and stochastic acceleration of super-Alfvénic ions by magnetohydrodynamic waves in Jupiter's outer magnetosphere is derived. The formulation is based upon a quasi-conserved energy invariant of the adiabatic transport which applies to an isotropic distribution undergoing rapid pitch angle scattering by waves. An analytic solution to the double diffusion equation is obtained and numerical results are presented for two models of ion injection. The first model assumes S^+ and O^+ are injected throughout a broad region of space through photoionization of Jupiter's magnetospheric neutral wind and obtain an initial energy corresponding to the local corotation energy after pickup by the planetary magnetic field. The second model assumes a monoenergetic distribution of energetic protons is implanted in the middle magnetosphere by the action of field-aligned potential drops in Jupiter's auroral ionosphere. For both light and heavy ions the injection process creates a seed population of particles which are further accelerated non-adiabatically by the MHD waves and adiabatically through radial diffusion. A comparison of the theoretical results with a recent data analysis of Voyager low-energy charged particle measurements is made with very good agreement. It is demonstrated that the model gives a rigorous quantitative account of and definitive explanation for the high-energy ion component of Jupiter's magnetosphere.

This paper is a follow-up of paper #4 for application to Jupiter. The important modification is the treatment of ion acceleration by means of wave-particle cyclotron resonant interactions with low-frequency magnetohydrodynamic turbulence. MHD waves have been observed by spacecraft magnetometers to be present throughout the middle-outer magnetosphere 20–100 R_J and this type of non-adiabatic acceleration process is thought to be the primary means by which super-Alfvénic ions are accelerated to cosmic ray energies in the outer magnetosphere of Jupiter. The solution of the combined diffusion/acceleration equation is applied to the observations of the low-energy charged particle experiment which in a recent analysis has provided a deconvolution of the ion spectra into a light ion (proton) and heavy ion (S^+ and O^+) component. The comparison of the theoretical model with the measurements is very good and the model is also able to reproduce the spatial variation of the observed hot plasma pressure, density, and temperature profiles throughout the magnetosphere. The paper is deemed to be a major breakthrough in the physics of ion acceleration in planetary magnetospheres and we regard it as the standard by which other theories and models will be judged for some time to come.

B. Presentations at Meetings:

1. Barbosa, D. D. and W. S. Kurth, Generation of plasma waves in Saturn's magnetosphere, *EOS Trans. AGU*, 73 (Supplement), 261, 1992.

2. Barbosa, D. D., "Plasma Waves in Planetary Magnetospheres", UCLA/IGPP Space Science Seminar, 1992.

3. Barbosa, D. D., "Acceleration of Energetic Ions in Jupiter's Magnetosphere", UCLA/IGPP Space Science Seminar, 1993.

4. Barbosa, D. D., "Morphology of the Jovian Aurora", UCLA/IGPP Space Science Seminar, 1994.

5. Barbosa, D. D., "Neutral Cloud Theory of the Jovian Nebula", UCLA/IGPP Space Science Seminar, 1995.

C. Patents and Inventions: NONE